Silica Fiber Lasers and Amplifiers as Pump Sources for Frequency Conversion

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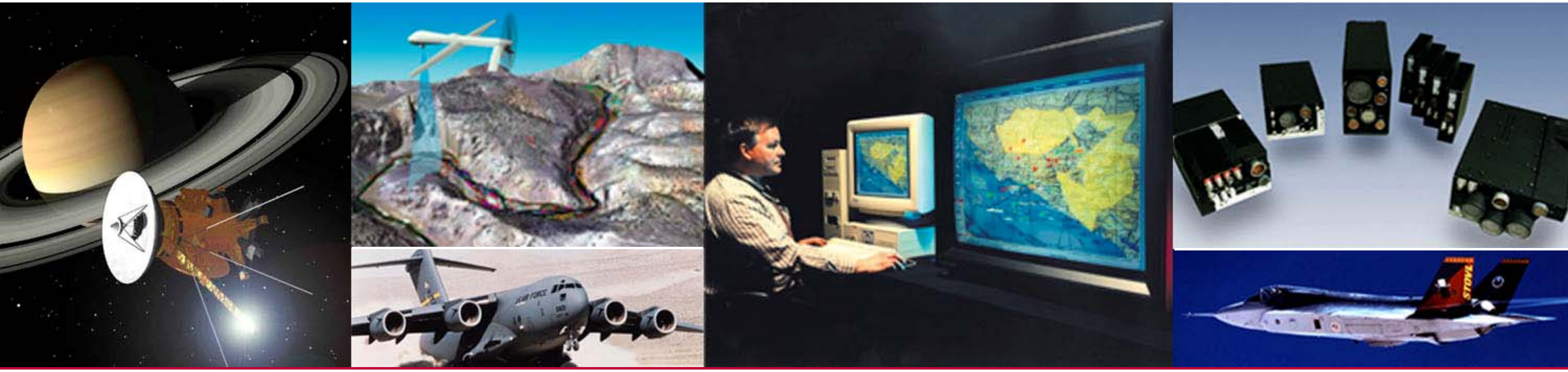

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Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

Outline

- Brief Overview of Nonlinear Conversion
  - Nonlinear materials, pump sources
- General fiber overview
- Design constraints and limitations
  - Nonlinear effects in fiber
- Considerations for fiber used in nonlinear conversion
  - Yb, Er, Er:Yb, Tm
    - Advantages and disadvantages
    - Fiber geometries
    - Architectures
- Summary
- General issues
- Moving forward

Mid-IR Generation

- Traditionally, Mid-IR light is frequency shifted from a laser pump
  - Diode-pumped solid-state laser converted in a nonlinear crystal
    - Typically ZGP, PPLN, OPGaAs
- How can we use fiber with Mid-IR light
  - We can use it to transport Mid-IR light over several meters
    - Fluorides and chalcogenides for power distribution
    - Advantages: only fibers which can transport MWIR light with low loss
    - Disadvantages: multimode output spoils beam quality
      - Not necessarily bad for most applications
  - However, we can use traditional fiber as a pump source
    - Take advantage of silica fiber technology
    - Transport the pump to nonlinear converter

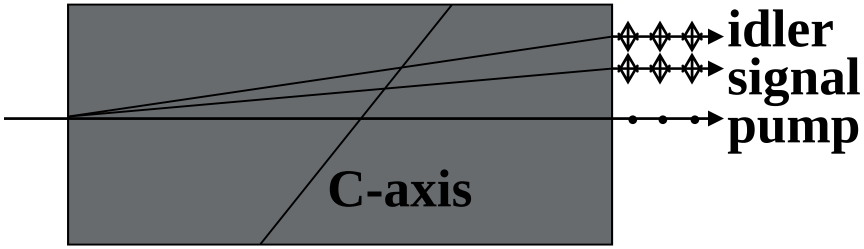
What is Needed For Mid-IR Generation?

- Pump source
  - Bright, single-mode laser
    - Generally need $M^2 < 2$
  - High peak power pulses
    - Generally several kW peak
  - Polarized output
    - For phase matching in nonlinear material
- Nonlinear material
  - Phase-matched to the pump and wavelengths to be generated
    - Conservation of energy and momentum
  - Critically phase-matched vs QPM materials
  - Conversion: methods: OPO, OPG, OPA

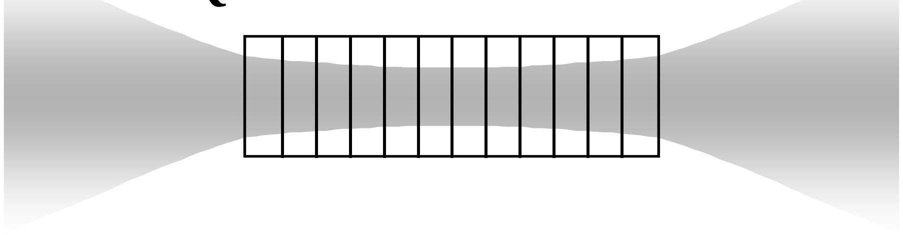
Nonlinear Optical Crystals – What Is Needed

- Higher efficiency and output power in the 2-8μm spectral range
- Mid-IR crystals compatible with common pump lasers
- Better long-wavelength materials for CO_2 doubling and 8-12μm generation
- Desirable material properties:
  - High nonlinear coefficient
  - Low absorption loss
  - High laser damage threshold
  - Low thermal lensing
  - Low/no walk-off
    - Non-critical phase matching (NCPM)

Birefringence Crystals

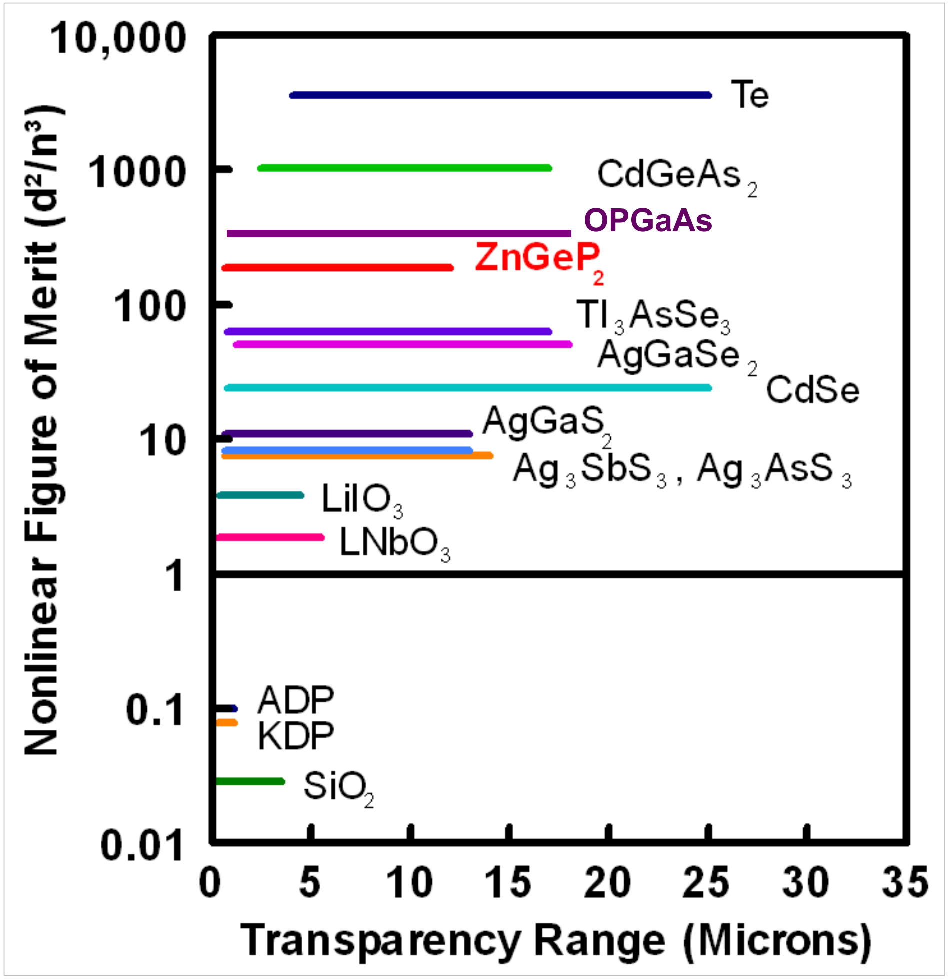


QPM Semiconductors



Common Nonlinear Materials for Mid-IR Conversion

- PPLN
  - Mature material, QPM
  - Limited transparency range in MWIR
- ZGP
  - High nonlinear coefficient
  - Critically phase-matched
- OPGaAs
  - QPM, high nonlinear coefficient
  - Large transparency range
  - Low absorption
  - High thermal conductivity



Solid-state vs. Fiber Pump Lasers

- Solid-state lasers
  - Q-switched
  - Good beam quality – M^2: 1.2-2.0
  - Lower repetition rates, long pulse widths
    - Trade-off between pulse width and PRF
  - Generally high pulse energy with high peak power
- Fiber lasers
  - Excellent beam quality – M^2: 1.0-1.5
  - Efficient, compact
  - Minimal/no free-space optics
  - Variable rep rates and short pulse widths →
    - Low pulse energy with high (or low) peak power
  - Wavelength flexibility
  - Power scalable with beam quality

Larger pump spots to mitigate NLO crystal damage

Smaller pump spots for high peak intensities

So Why Bother With Silica Fiber?

- It can efficiently generate high powers and transport pump light
  - Transparent from near-IR (<800nm) up into mid-IR (2100nm)
- Gain length
  - Distribute the gain (lower gain per unit length, longer length)
  - Spread the heat load over long fiber length (surface area for heat removal)
- Frequency agility
  - Glass has a very chaotic structure
    - Broad absorption and emission features compared to crystals
- Efficient pump/signal overlap
  - Let the waveguide do the work
- It is inexpensive (in large quantities)
  - Leverage the telecom investments
    - Splicing, diodes, components, etc.
- The light is entirely confined to the fiber

For High Power Operation

- DPSS crystal-based technologies
  - Thermal lensing in crystal
  - Beam distortions at high powers
  - Need *significant* waste heat removal
    - This requires a major engineering effort and increases size, weight, power

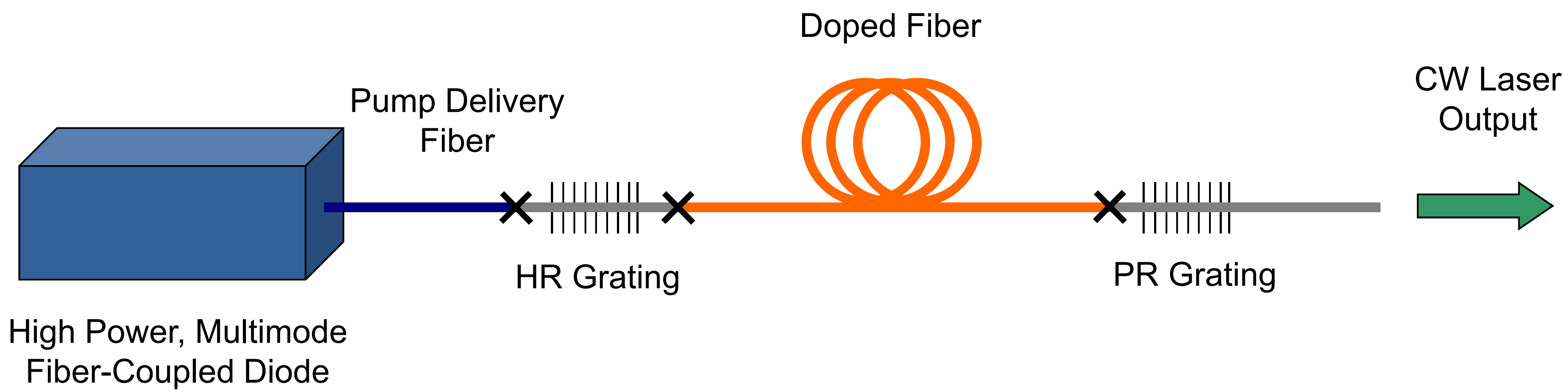
- Fiber
  - Pump absorption is spread over a few meters rather than a few centimeters
  - Fiber core is close to the heat-sink
    - Only a few hundred microns
  - Architectures can be power scalable without significantly impacting beam quality

Typical Fiber Dopants

- Erbium (Er)
  - Low gain, but eyesafe emission at 1.55μm → telecom wavelengths
  - Can pump at 980nm or resonantly at 1470-1532nm
- Ytterbium (Yb)
  - Very high gain, very efficient
  - Emission from 1000-1150nm (typically used from 1035-1080nm)
  - Can pump from 915nm-975nm
- Ytterbium-sensitized erbium (Er:Yb)
  - High power emission at 1.55μm → higher gain due to Yb ions
  - Pumped from 915nm-975nm
- Thulium (Tm)
  - 2-micron emission from 1850-2100nm
  - Pumped at 795nm or 1550nm
- Thulium-Holmium (Tm:Ho)

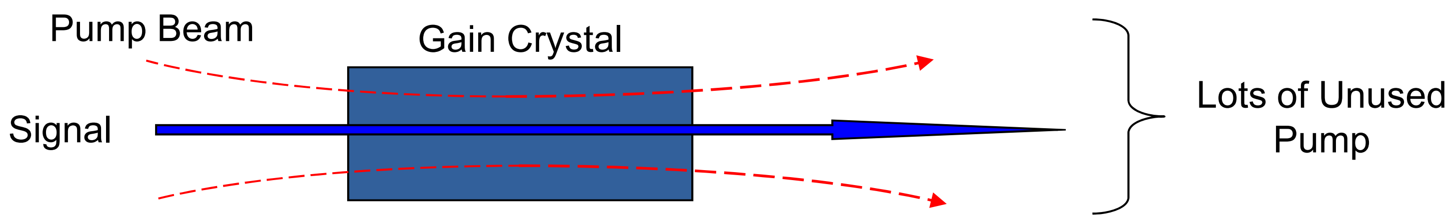
Fiber Lasers

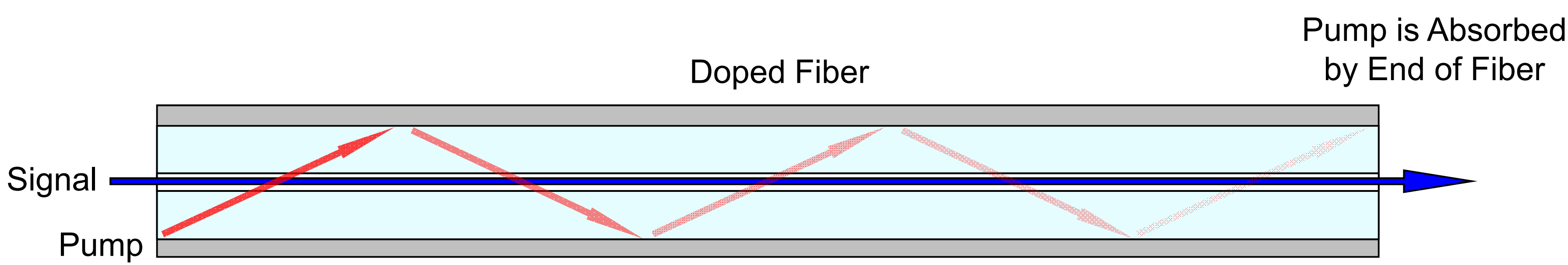
- Just like a solid-state laser, but the fiber is the gain medium
  - Instead of a crystal and mirrors, we have a fiber and gratings
  - Diode pumps the fiber to excite the active ions
  - Gratings provide feedback at a specific wavelength for oscillation
  - Typically CW operation
    - But they can be q-switched or modulated
  - Have very closely spaced modes due to long cavity lengths
    - Typically several meters



Amplifier Operation

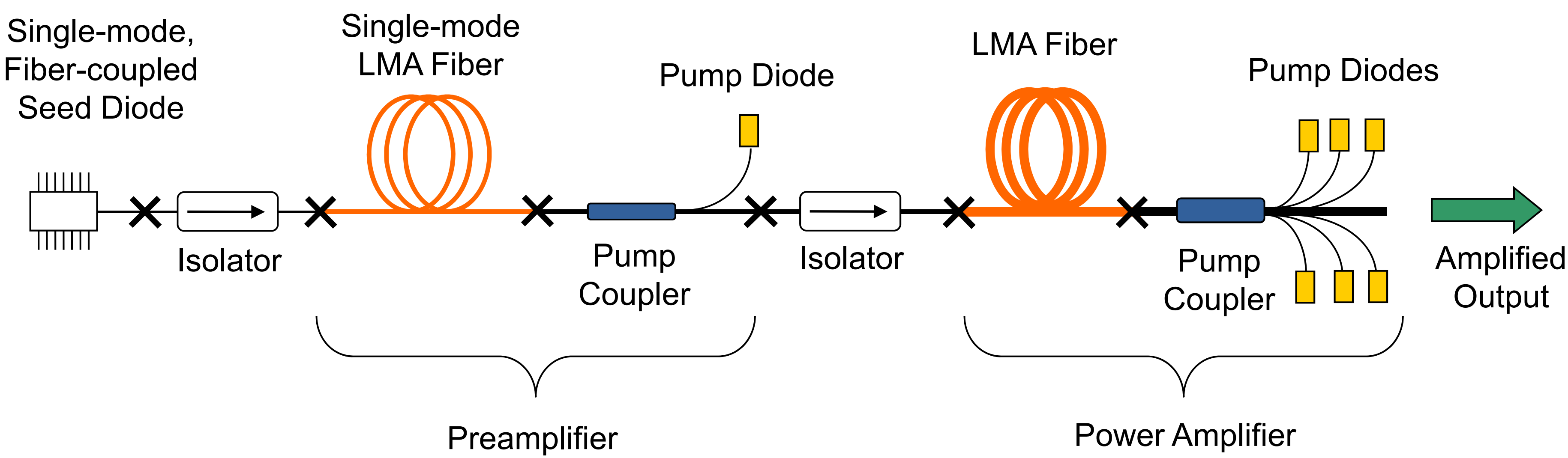
- Just like a solid-state amplifier (all about overlap and saturation)
  - But you don't have to mode-match the signal and the pump
  - The waveguide does this for you
    - Length is determined by the core/clad area overlap
      - And thus, the pump/signal overlap





Fiber Amplifiers

- When seeded, fibers make very efficient amplifiers
  - Offer much more gain than crystal amplifiers
    - Due to length of gain medium
    - Fiber amplifier typically offer gains ranging from 5-20dB
  - The ability to generate pulsed output from a fiber
    - By seeding with a pulsed source (diode, microchip laser)



Performance

- Very high efficiency
  - Due to gain length and core/clad overlap (signal/pump overlap)
  - All of the pump is used (and all the gain is in the core)
- CW operation
  - Yb-doped CW fiber systems have demonstrated >75% optical efficiency
  - Er-doped systems are ~30% efficient (low power)
  - Er:Yb-doped are ~35% efficient (high power)
  - Tm-doped fibers are approaching 60% efficiency
- Pulsed operation
  - High peak-powers are achievable rather efficiently
    - Slightly less efficient than CW, but still much better than DPSS systems
      - Due to low duty cycles
    - Nonlinear effects become a major issue
      - This is where the engineering comes in

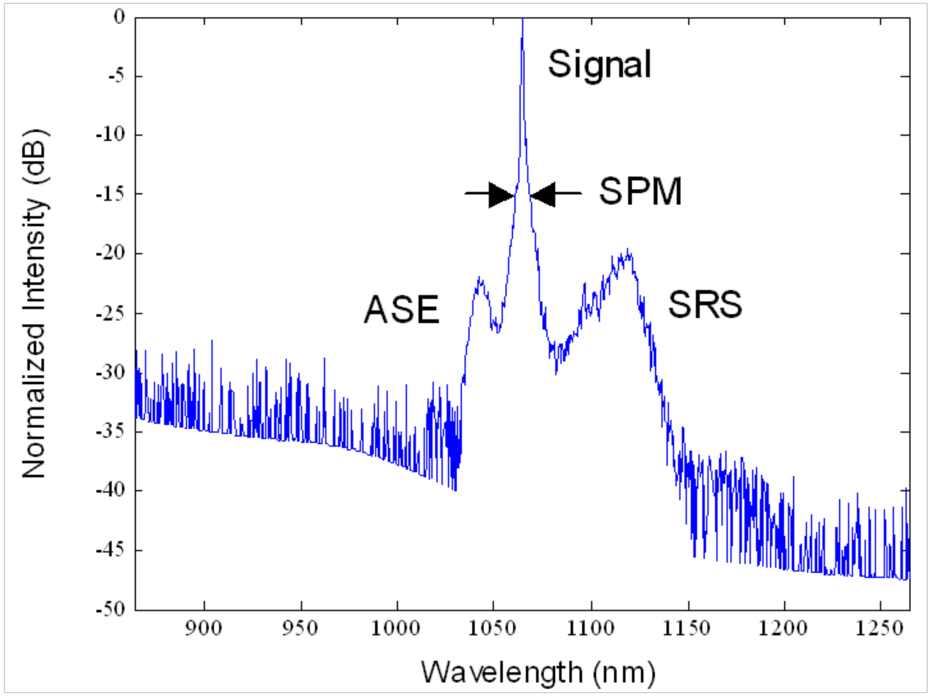
Limitations of Fiber Systems

Energy Scaling

- What are the limits?
  - Fiber core size - high powers do not like to be confined to such a small area
    - 10W average (10kHz, 10ns) in a 30um core = 14GW/cm^2
- Self-focusing limit
  - High intensities modulate the nonlinear refractive index in the core
  - This can form a Kerr lens and focus the light until the fiber breaks
  - The limit for silica fiber is ~4.5MW of peak power at 1064nm
    - Does not depend on core size → we have length on our side again
- Surface damage
  - Occurs at the glass-air interface as the light exits the fiber
    - Depends on the surface quality and the pulse width but a good rule of thumb is <4GW/cm^2
- Bulk damage
  - Depends on the peak power, pulse width, and core size (~600GW/cm^2)
- Nonlinearities in the fiber

Nonlinear Effects

- Fibers have one particular “limitation”
  - Small cores yield very large optical intensities
  - Consequently, the good things about fiber are also bad
    - Small cores and long lengths may induce nonlinear effects
- What are these effects?
  - Stimulated Raman Scattering (SRS)
  - Stimulated Brillouin Scattering (SBS)
    - Single frequencies
  - Self-phase Modulation (SPM)
    - Optical Kerr effect
    - Nonlinear phase shift
  - Four-wave Mixing (FWM)
    - $X^{(3)}$ susceptibility
- Solutions?
  - “Short” fiber lengths, large cores
  - Novel fiber geometries



Now for the Math...

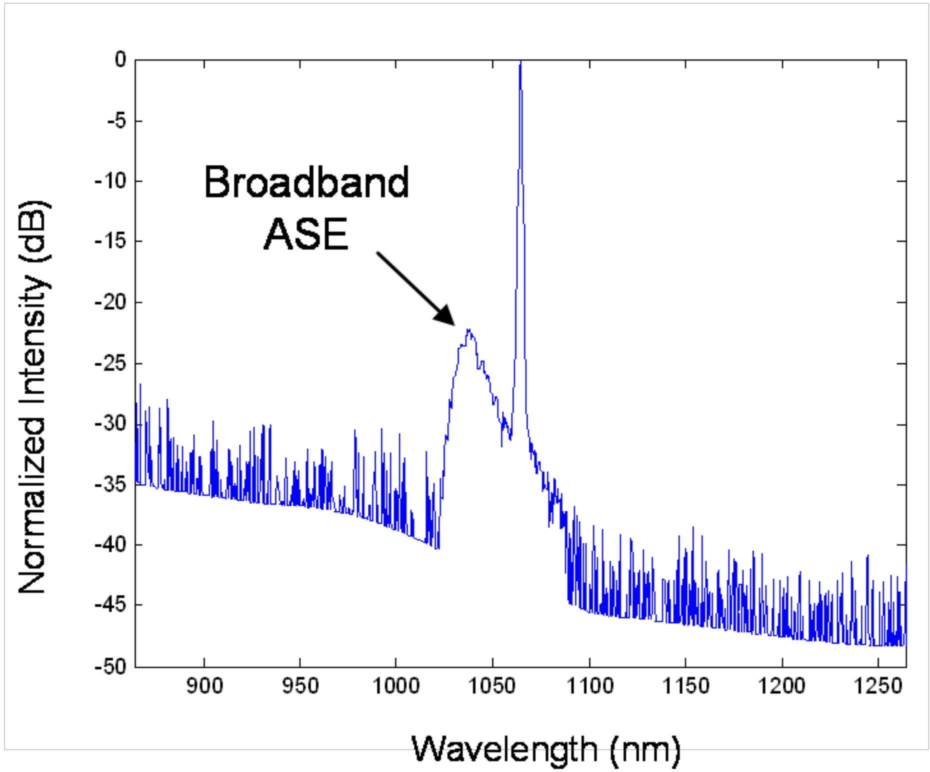
$$P_{SRS}^{thr}(\lambda) \approx \frac{16 \cdot A_{eff}}{g_R(\lambda) \cdot L_{eff}} \qquad P_{SBS}^{thr}(\lambda) \approx \frac{21 \cdot A_{eff}}{g_B(\lambda) \cdot L_{eff}} \cdot \left(1 + \frac{\Delta \nu_s}{\Delta \nu_B(\lambda)}\right)$$

$$\Phi_{SPM} = \frac{2\pi n_2}{\lambda A_{eff}} P L_{eff}$$

- All effects are a function of fiber length, core size, and wavelength
  - Shorter fibers, larger cores increase the nonlinear thresholds
  - The longer the wavelength, the higher the threshold
- Example
  - Pulsed Yb-doped fiber amplifier at 1064nm (10kHz PRF, 10ns pulses)
    - Core diameter = 15um; fiber length = 5m; $g_R = 1 \times 10^{-13}$ m/W
    - P_{SRS}=6.5kW → average power of 650mW is above the SRS threshold

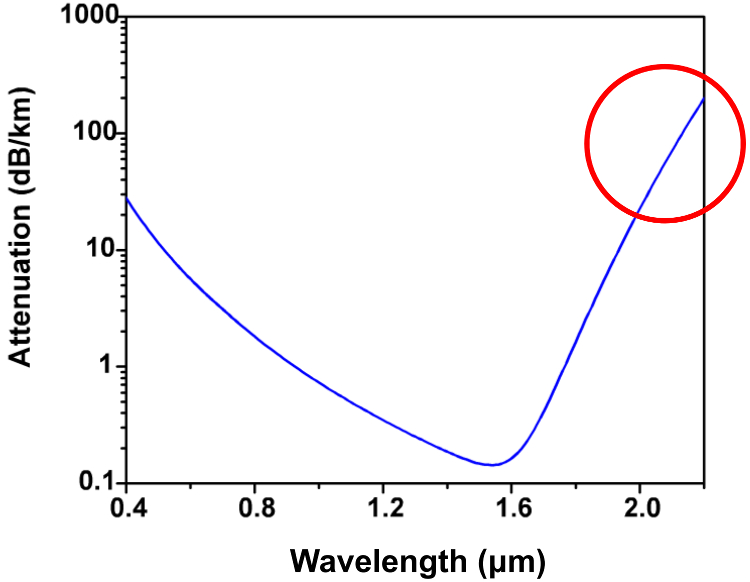
Amplified Spontaneous Emission (ASE)

- The excited ions have to go somewhere
  - If not extracted, the excited electrons decay and spontaneously emit
  - Unfortunately, there is gain at the emission wavelengths
    - So the spontaneous photons see gain and get amplified
    - This reduces the amount of gain seen by the signal, thus reducing efficiency
- Solution
  - Filter the out-of-band ASE
  - Saturate the gain so the signal extracts most of the pump



Background Losses in Silica

- Fibers have lowest loss in 1.55µm window (telecom)
- Relatively low loss in 1.0µm region
- Above 1.6µm, losses are getting higher
- Above 2.1µm, background loss is becoming significant (>0.1dB/m)
    - For lasing, this means higher threshold for lasers
    - Shorter fiber lengths would be required for efficient operation
    - Higher propagation losses in passive fiber
        - Limits propagation distances
        - 10m transport = 20% power loss



G. Frith, et al., Photonics West (2008)

So What are Silica Fibers Systems Good For?

- High average power, low pulse energy output
  - With diffraction-limited performance
  - Higher repetition rates (<50kHz to >1MHz)
  - High efficiency → far better than DPSS lasers
  - Peak power output depends on pulse width and PRF
- Fibers make the perfect pump source for frequency conversion
  - Excellent beam quality
    - Determined by the fiber geometry
  - Wavelength agility (not offered in crystal systems)
    - Yb fiber offers more than 100nm of gain
    - Tm offers more than 200nm
  - Pulse flexibility
    - Pulse width and PRF variability
- Manufacturability
  - You can splice these fibers together and eliminate free-space transitions

Considerations for Nonlinear Conversion

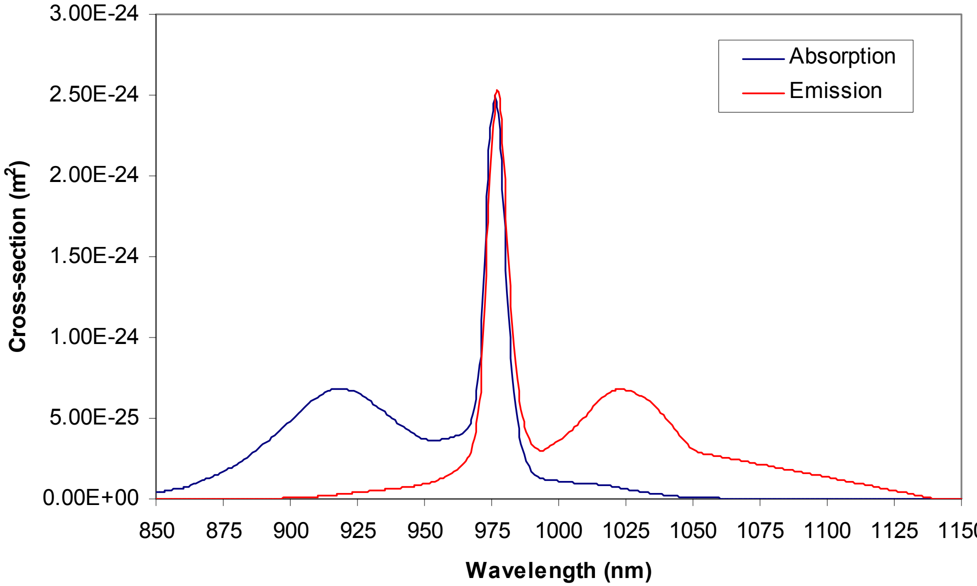
What are Needed from Fibers for Conversion

- Need to match the pump laser with nonlinear material
  - Gain region in fiber with the nonlinear material
  - Yb with PPLN
  - Er:Yb with PPLN
  - Tm with ZGP, OPGaAs

- Need energy and peak power for conversion
  - Nonlinear materials only care about peak intensity/energy
  - These are not energy storage devices
    - Conversion only occurs on a pulse-to-pulse basis
  - This translates to either high peak power or high intensities
    - By focusing tightly into nonlinear material

Ytterbium-Doped Fiber Systems

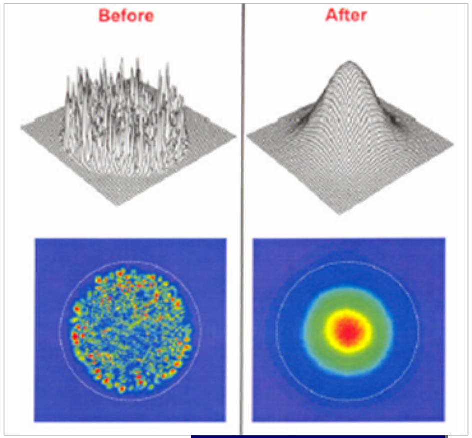
- Advantages:
  - High efficiencies (>70%)
  - Low quantum defect
    - Pumping from 915-976nm
    - Lasing from 1040-1080nm
  - Common wavelengths
- Primary Nonlinearities:
  - SRS, SBS, SPM, FWM
- Challenges:
  - Peak power scaling due to nonlinear effects
- How to get high peak power:
  - Large fiber cores, short fiber lengths
  - Novel fiber geometries

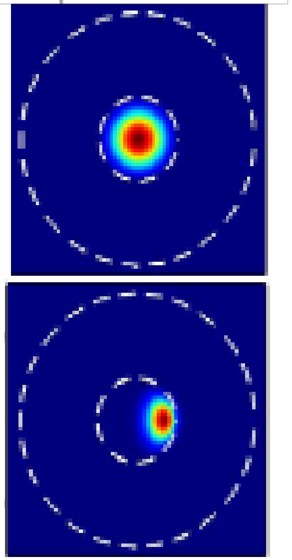


Ytterbium Fiber Geometries

- Large Mode Area (LMA)
  - Large core (15-30μm) with low NA (0.06-0.1)
  - Up to 80μm has been reported (U. Michigan)
  - Advantages:
    - Coiling promotes single-moded operation
    - HOMs get coupled into cladding
    - Conventional splicing technology can be used
  - Disadvantages:
    - Coiling can artificially reduce mode size in the core
    - Larger cores can support higher order modes
      - Even with coiling
    - Cannot scale to very large cores due to limited NA range
      - Difficult to reduce NA below 0.06
      - Splicing is difficult for cores above 25μm diameters

D. Kliner, et al., SPIE OE Magazine (2004)

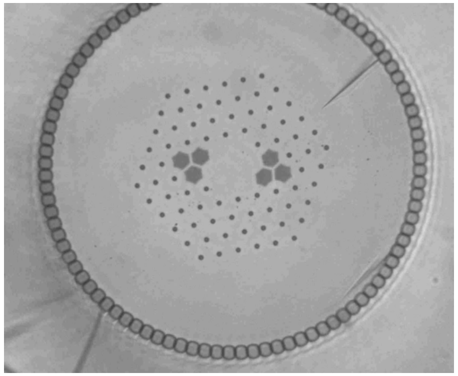




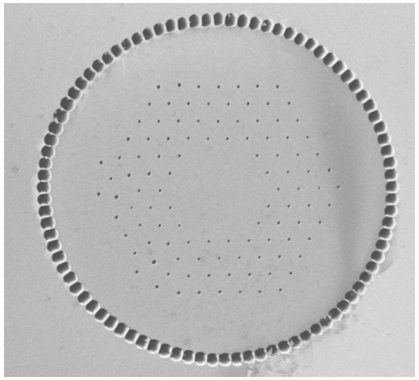
J.M. Fini, Opt. Exp. 14, 69 (2006)

Ytterbium Fiber Geometries

- Photonic Crystal Fiber (PCF)
  - Very large core (>40um) with low NA (<0.03)
    - Air holes tailor the NA
  - Advantages:
    - “Endlessly” single-mode operation
    - Significantly larger core diameters than LMA fibers
      - Promotes power scaling with higher nonlinear thresholds
  - Disadvantages:
    - Coiling limitations
      - Low NA promotes significant bend-losses
        - For fundamental mode
      - Requires >25cm bend radii
    - Air holes are present around the core
    - Cannot splice without collapsing air holes
      - Need free-space transition



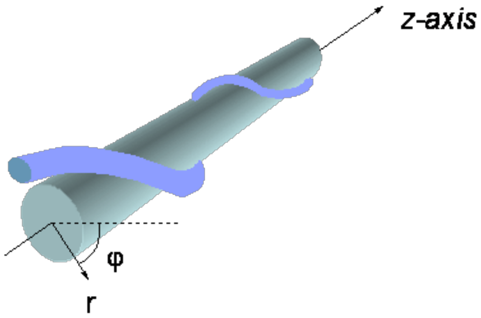
F. Di Teodoro and C. D. Brooks, ASSP (2006)

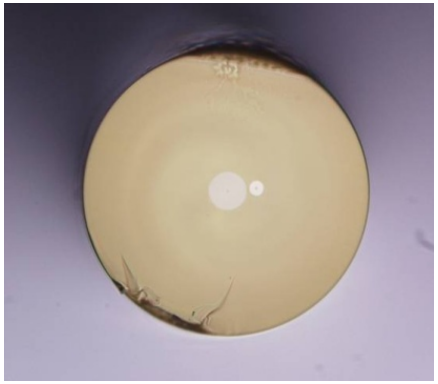


J. Limpert, et al., Opt. Express 14, (2006)

Ytterbium Fiber Geometries

- Chirally-Coupled Core (CCC)
  - Large core with low-moderate NA
    - Helical coupled core
      - HOM suppression
  - Advantages:
    - Higher order modes see loss due to CCC
    - Significantly larger core diameters are achievable than LMA fibers
      - Promotes power scaling with higher nonlinear thresholds
    - Can use with conventional splicing technology
  - Disadvantages:
    - Relatively new technology
    - Need to develop components with matching passive fibers
    - Bend radii can be large (15cm for 35um core)
      - To avoid distortion in the fiber core
      - Results in larger packages

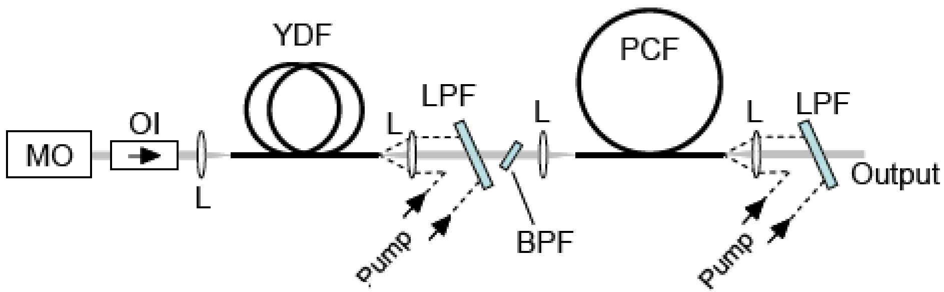




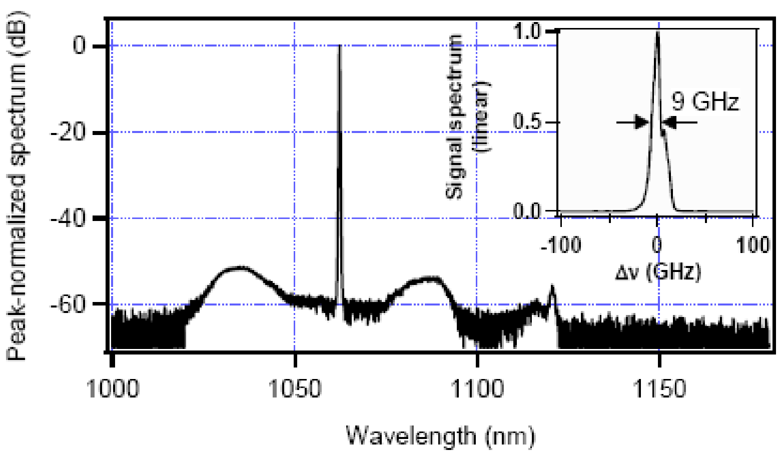
C. Liu et al., ASSP (2007)

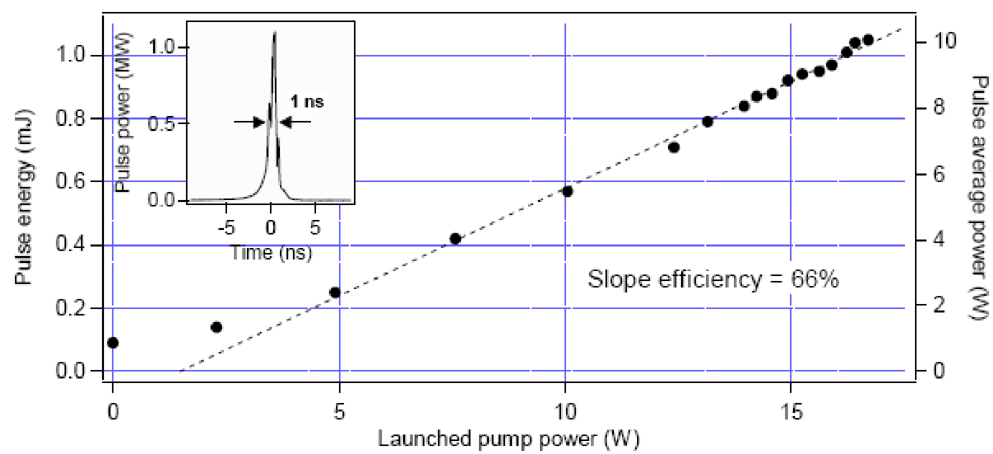
High Peak Power YDFA

- MOPA architecture
  - Seeded by a microchip laser
- 10W average power, 9.6kHz PRF, 1ns PW
  - 1mJ pulse energy, 1MW peak power



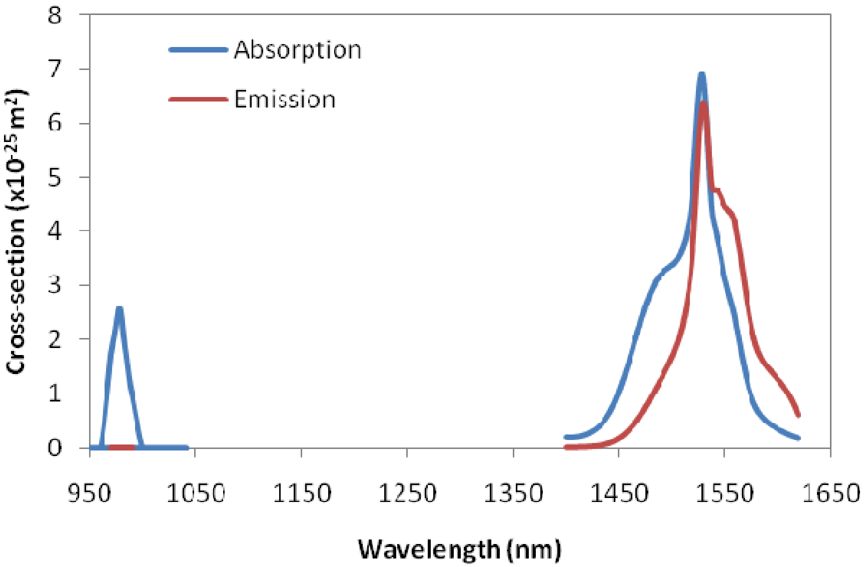
F. Di Teodoro and C. D. Brooks., ASSP (2006)

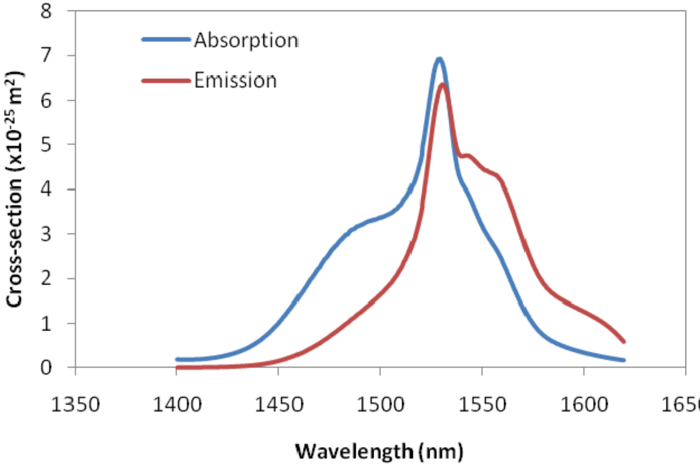




Erbium Fiber Systems

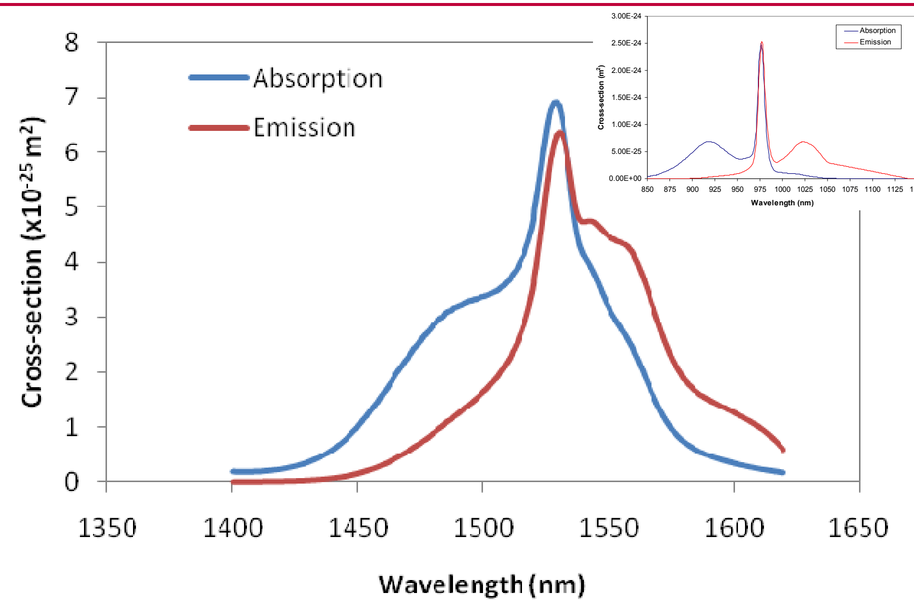
- Advantages:
  - Eyesafe output in the 1.55um region
    - Lasing from 1525-1575nm
  - Leverage telecom technologies
- Primary issues:
  - Low gain
  - Doping is limited due to quenching
- Challenges:
  - Absorption is low at 980nm
    - Requiring long fiber lengths
  - Diode brightness limitations
    - Resonant pumping at 1470nm adds promise to Er-only fibers
      - But diodes are inefficient and not bright enough for high power

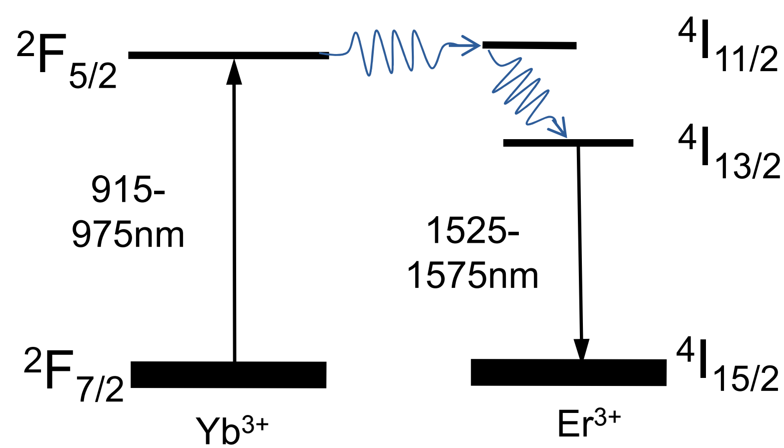




Erbium-Ytterbium Fiber Systems

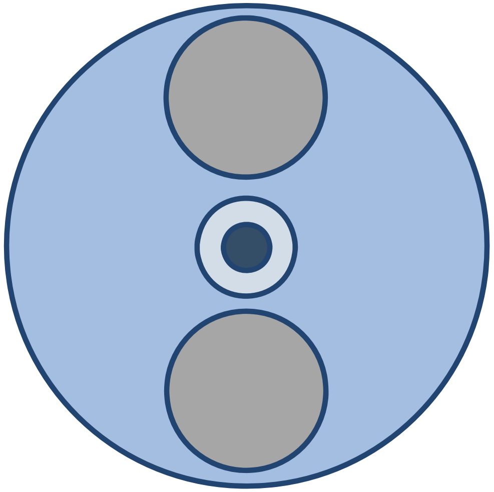
- Advantages:
  - Eyesafe output in the 1.55um region
    - Lasing from 1525-1575nm
  - Pump with diodes used in Yb
    - 915-975nm
- Primary issues:
  - Energy transfer from Yb to Er
  - 1-micron ASE and parasitic lasing
- Challenges:
  - Power scaling
    - NA limitations
    - Yb lasing





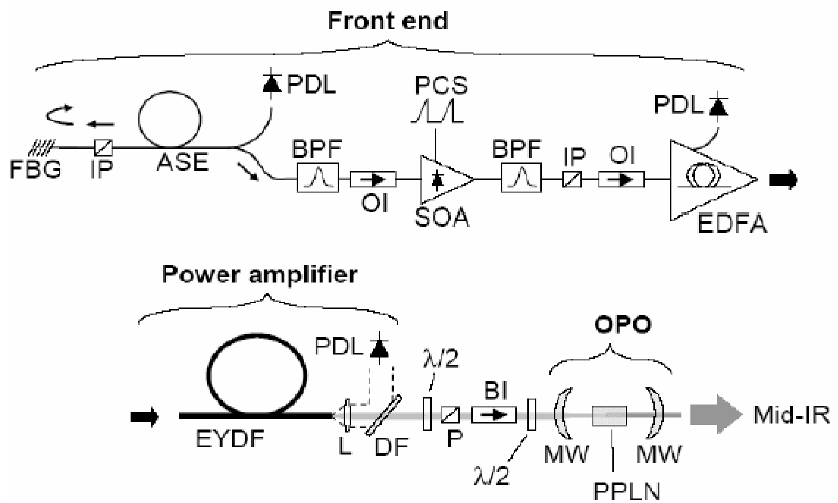
Erbium-Ytterbium Fiber Geometries

- Pedestal Fiber
  - Co-doping increases index in the fiber core
  - A “pedestal” surrounding the core can reduce the NA in the core
  - Advantages:
    - Lower NA core compared to non-pedestal LMA designs
    - NAs of 0.1 have been achieved
  - Disadvantages:
    - Additional glass material in the fiber
      - Fusion splicing issues
    - NA cannot be reduced indefinitely
      - Limits power scaling with SM operation

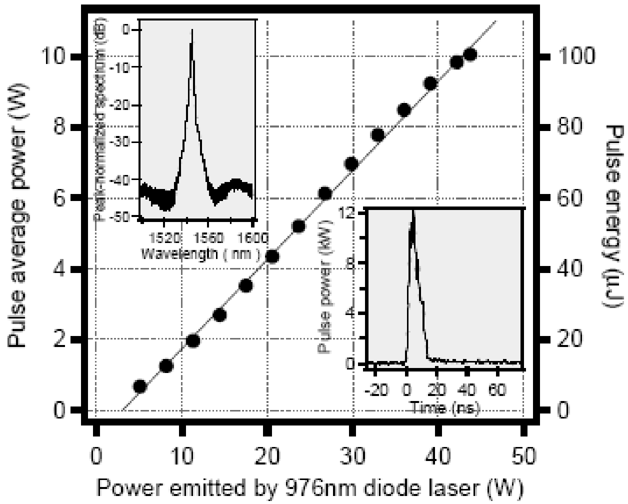


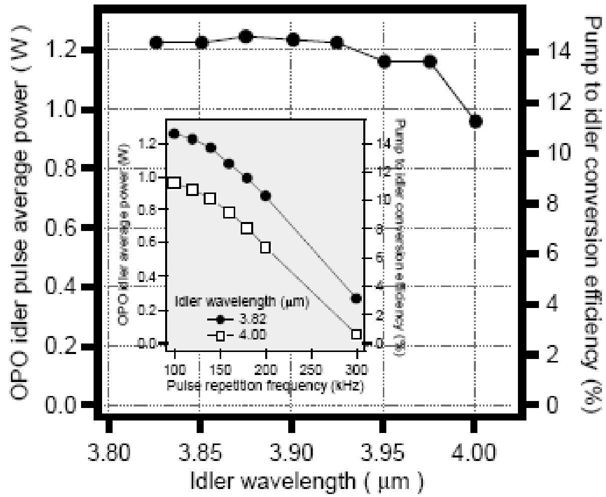
Pulsed Er:Yb Fiber Amplifier

- Pulsed MOPA
  - Generating 10W average output power
    - ~8ns pulses at 1545nm
- Converting to MWIR in PPLN
  - 10mm long crystal
  - 1.2W average MWIR power



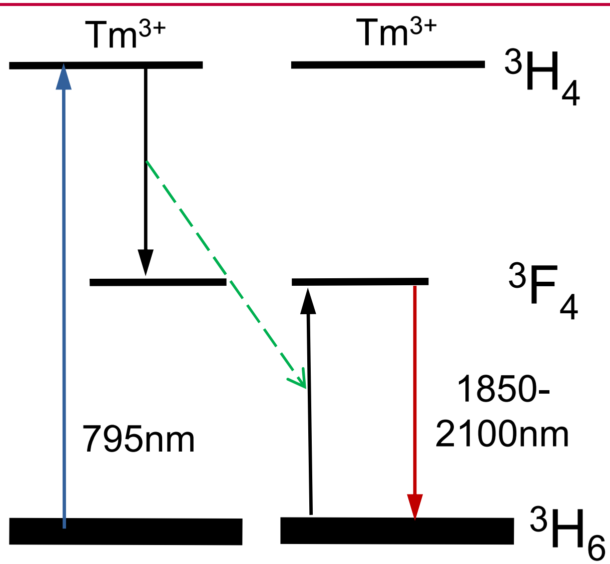
F. Di Teodoro and S. Desmoulins, CLEO (2007)

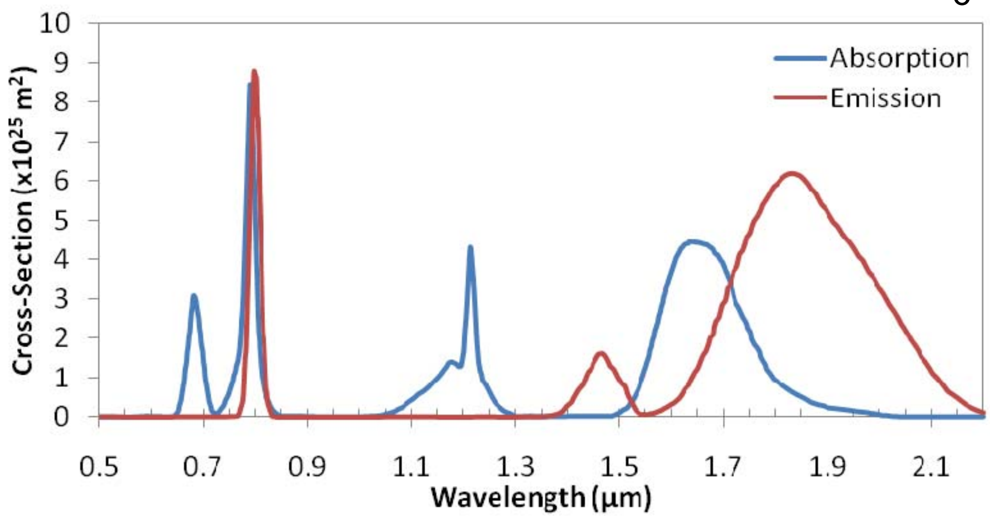




Thulium Fiber Systems

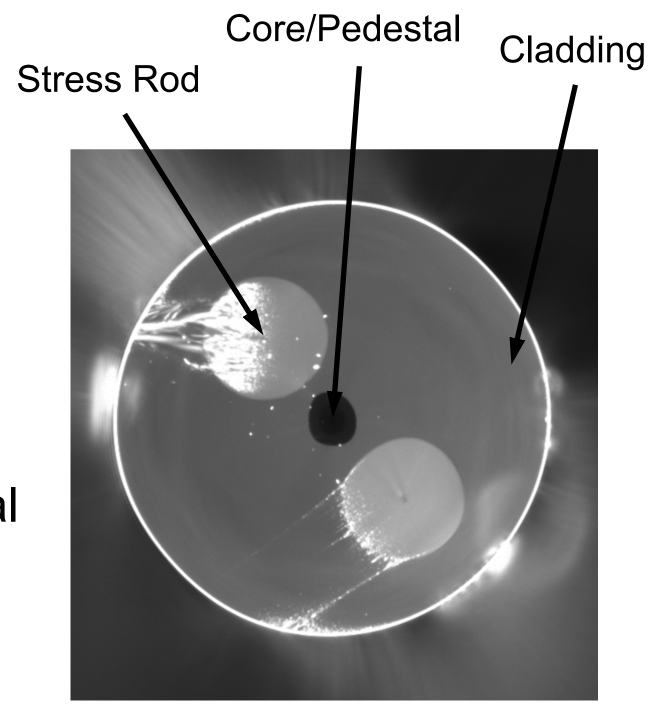
- Advantages:
  - High efficiencies
    - Due to 2-for-1 cross-relaxation
    - Pumping at ~795nm
  - Direct eyesafe output in the 2-micron region
    - 1850-2100nm
- Primary nonlinearities
  - FWM, SPM
- Challenges:
  - Power scaling
    - Due to NA limitations
      - Aluminum doping



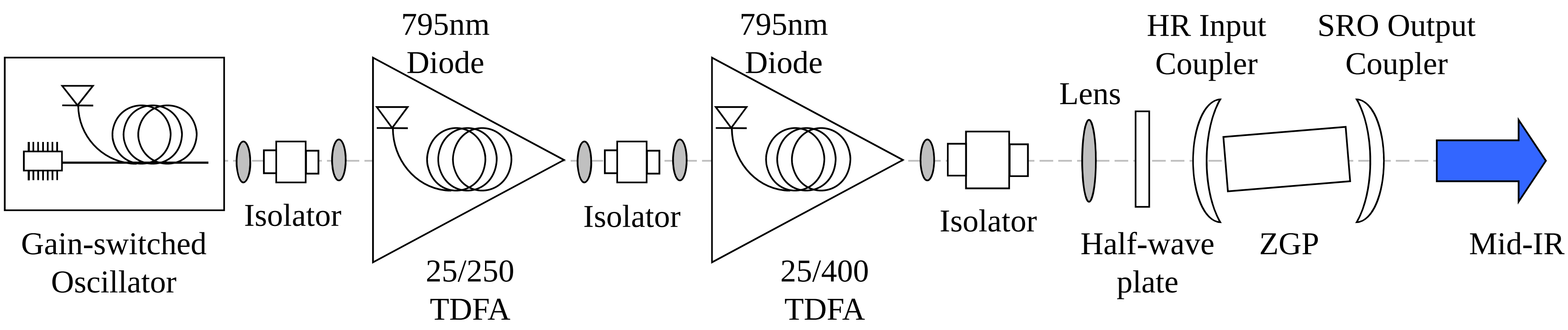


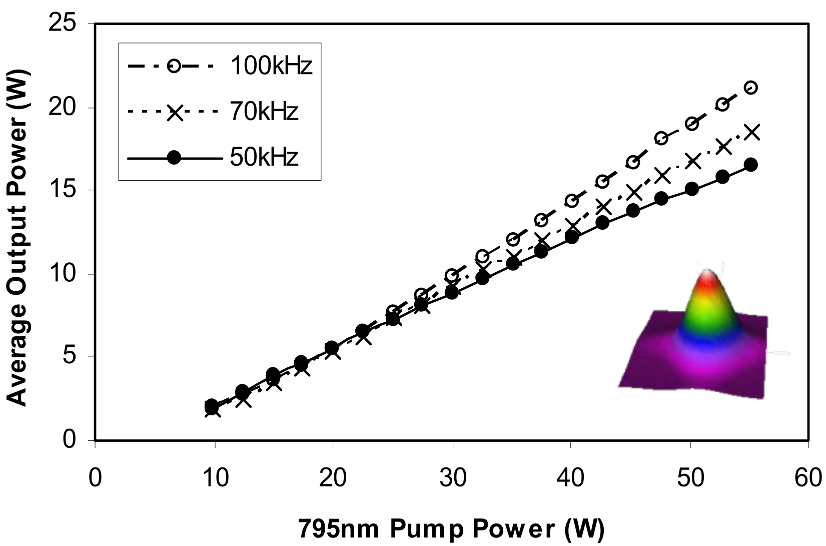
Thulium Fiber Geometries

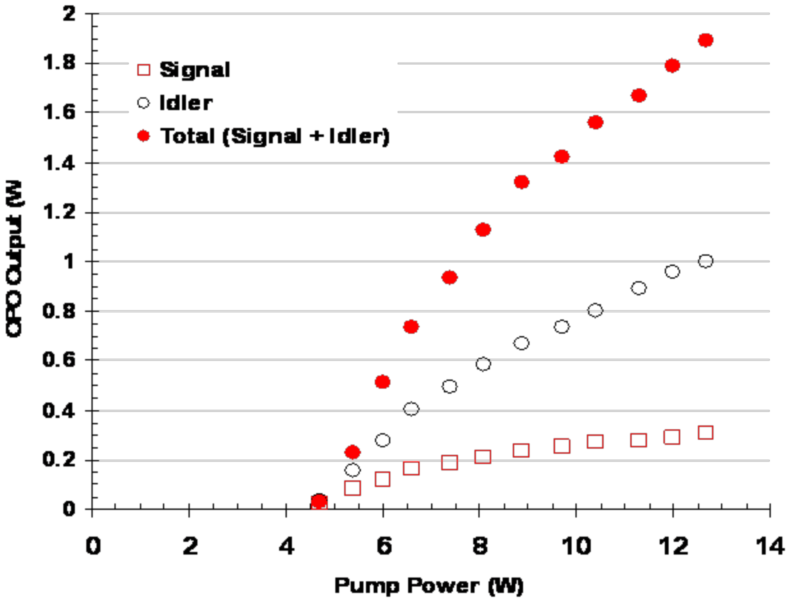
- Tm fiber geometries
  - LMA-pedestal
- To get high efficiencies in thulium
  - Must get ions to cluster
  - Dope core with aluminum ions
    - Causes index/NA to increase
  - Surrounding the core with an undoped pedestal
    - Drops the NA of the core
      - With respect to pedestal
  - Disadvantages:
    - Additional glass material in the fiber
      - Fusion splicing issues (4 glasses in a PM fiber)
    - NA cannot be reduced indefinitely
      - Limits power scaling with SM operation



TDFA Pumped Mid-IR ZGP OPO



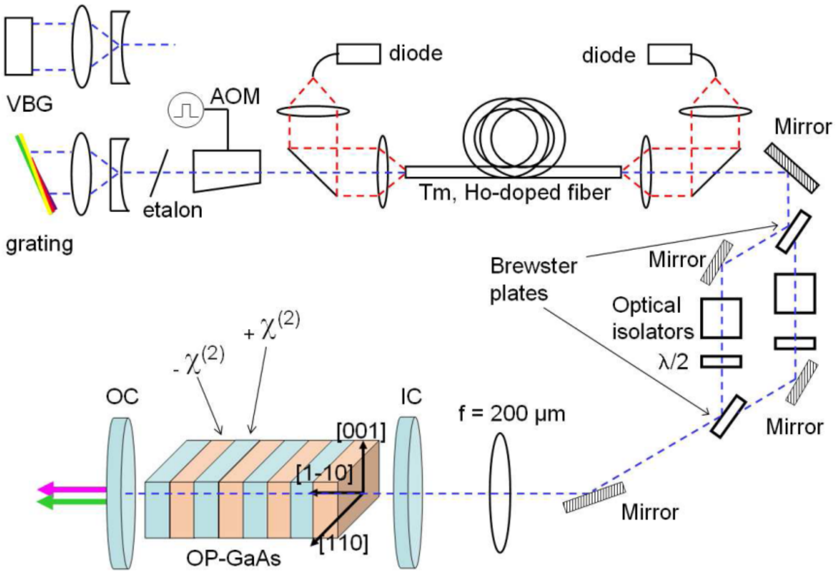


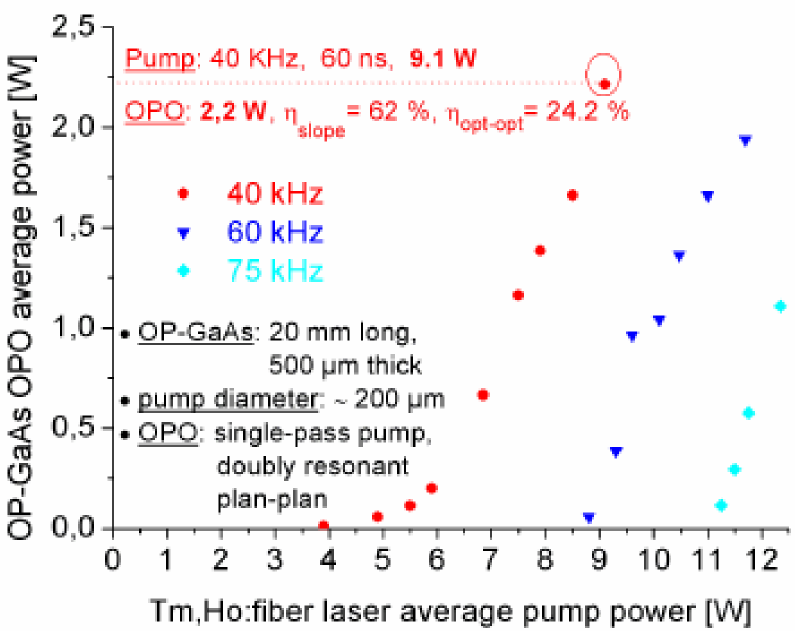


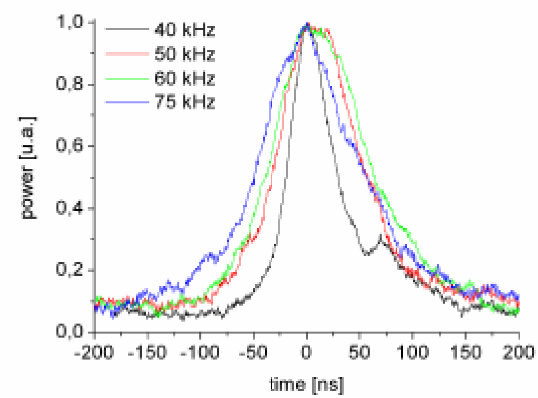
D. Creeden, et al., SPIE Defense and Security (2008)
D. Creeden, et al., Opt. Lett. **33**, 315-317 (2008)

TDFL Pumped Mid-IR OPGaAs OPO

- Q-switched Tm:Ho fiber laser
  - Grating used to narrow output spectrum
- Pumping OPGaAs for MWIR generation
  - 2.2W mid-IR output power







C. Kieleck, M. Eichhorn, et al., CLEO (2009)

Summary

- Must tailor the fiber pump to the nonlinear material
  - Nonlinear material will drive fiber dopant selection
- Must design fiber system around nonlinear effects
  - For nonlinear conversion, we must generate peak power
    - Without running into nonlinear effects in the fiber
  - Need novel fiber geometries or clever architectures
    - To achieve high enough peak powers to convert
- We are currently at the limit of conventional technology
  - Limited by components, doped fiber, free-space coupling
  - Ideally, we need all-fiber solutions

General Issues

- Nonlinear effects
  - Need to trade-off nonlinear thresholds in the fiber with the peak-power requirements of the frequency converter

- Brightness of pump sources
  - To keep gain lengths relatively short you need a high core/clad ratio
    - Either means large core or small cladding

- Beam quality from LMA fibers
  - LMA fibers cannot scale indefinitely
  - Eventually higher order modes will prevail
  - This leads to other fiber geometries (CCC, PCF)
    - But we need components and architectures which mate with these new fibers

General Issues

- Components
  - Passive fibers to match active fibers
  - Isolators, taps, pump combiners, diodes, etc.
- Fiber geometries
  - LMA fibers have scaling issues
    - The larger the core, the lower the NA
    - Limits coiling, mode can get distorted by coiling (reducing mode area)
  - Pedestal designs are difficult to splice to
    - 3-4 different glass compositions in a single fiber
      - Each with a slightly different melting point
- More research into other dopants
  - Ytterbium is very common, but is the farthest away from the mid-IR
  - Thulium and holmium are promising for mid-IR generation
    - Offering high efficiency with wavelength advantages

Path Forward

- More emphasis needs to be placed on component and fiber development
  - Currently there are few commercial vendors of specialty fibers
    - Especially for Thulium or Holmium-doped fibers
  - Also few vendors for components

- Every time a new fiber is made, new components need to be developed
  - Limits the turn-around time from new fiber development to its implementation in a system
    - Need pump combiners and isolators compatible with the fiber

- Ideally, everything needs to be fiber-coupled
  - To eliminate free-space coupling
  - Free-space coupling into small-core fibers is not practical in real-world systems